Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project Internal Reference:

Project: DECAM

Title: Focal Plate Thermal Analysis

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Abstract Summary:
The multi-CCD Test Vessel has a full scale prototype focal plate to support CCDs. A focal plate flatness requirement is 30 microns. A theoretical case where the focal plate and bipods are studied independently without the full vessel is analyzed. Temperature gradients and distortions due to temperature gradients are presented.

Applicable Codes:
N/A

Introduction:

The multi-CCD Test Vessel has a full scale prototype focal plate to support CCDs. The Focal Plate is 1.38 inch thick aluminum 6061. The aluminum plate is supported by 4 bipods. The bipod material is Ti-6-Al-4V. The bipods also thermally isolate the cold focal plate from the warm camera vessel shell. Crude hand calculations for thermal displacements of the focal plate due to the cool down are given. A Finite Element Model of the focal plate and bipods was constructed. Then, a series of FEA cases were performed. The nominal focal plate operating temperature is -100°C.

HAND CALCULATIONS:

Calculating the Z displacement of the Focal Plate During Cool Down:

The Z displacement of the focal plate is calculated assuming that the focal plate moves in Z due to the thermal expansion of the bipod legs. The Aluminum Focal Plate also shrinks when cooled down.

dL of the bipod leg is computed as:
dL = L * CTE * dT

Where:
L = Z distance between bipod support and the center line of the focal plate where the bipods attach = 0.16 meters (6.3 inches)
CTE of Ti-6Al-4V = 8.6 e-6 m/m °C
Temperature change from 20°C to -100 °C = dT = 120 °C
One end of the bipod leg stays warm so and average temperature change of 60 °C is used.

dL of the focal plate thickness is computed as:
dL = L * CTE * dT
dL = 0.16 M * 8.6 e-6 * 60 °C = 82 microns

dL = L * CTE * dT
L = Z distance between the center line of the focal plate where the bipods attach and the front surface of the Focal Plate = 0.0177 meters (.69 inches)
Average CTE of Aluminum 6061 in the temperature range = 20 e-6 m/m °C
Temperature change from 20°C to -100 °C = dT = 120 °C

dL = L * CTE * dT
dL = 0.0177 M * 20 e-6 * 120 °C = 42 microns

The Expected Z displacement of the front surface of the Focal Plate is expected to be:
dZ = 83 microns + 42 microns = 125 microns away from the C5 lens.

The FEA shows a Z displacement in the first case of 142 microns.

Calculating the Radial Shrinkage of the Focal Plate:

The radial shrinkage of the Aluminum focal plate is due to the temperature change during cool down.

Radius of the Focal Plate $= 0.2625$ meters (10.33 inches)
Average CTE of Aluminum 6061 in the temperature range $= 20$ e-6 m/m °C
Temperature change from 20°C to -100 °C $= dT = 120$ °C

$dL = L * CTE * dT$
$dL = 0.2625$ M $* 20$ e-6 $* 120$ °C $= 630$ microns

The FEA shows a radial shrinkage in the first case of 601 microns.

Calculating the Heat Load due to the Bipod Legs:

The heat transfer to the focal plate due to conduction of a single bipod leg is calculated.

Length of a bipod leg $= 0.1628$ meters (6.41 inches)
Diameter of leg $= 4.76$ mm (3/16 inch)
Area of leg $= 1.78$E-5 M^2
Average K of Ti-6Al-4V $= 6$ W/M.K
Temperature change from 20°C to -100 °C $= dT = 120$ °C
One end of the bipod leg stays warm so an average K is used

$Q = K*A*dT / L$
$Q = 6 * 1.78$E-5 $* 120 / 0.1628 = 0.076$ Watts per leg
Q for six legs $= 0.45$ Watts

Calculating the Bending Stress in the Bipod Leg:

The bipod leg bends when the focal plate shrinks radially differentially from the warm support ring. The radial shrinkage of the focal plate is 601 microns as given from the FEA. The bending stress in the bipod leg is calculated based on a cantilever with fixed end support and guided at the other end. The load on the beam is calculated based on a free end displacement 601 microns.

Load required to displace free end by 601 microns

$dL = 601$ microns
Length of a bipod leg $= 0.1628$ meters (6.41 inches)
$E = 114$ Gpa for Ti-6Al-4V
Diameter of leg $= 4.76$ mm (3/16 inch)
$I = 0.0049 * d^4 = 0.049 * 0.00476M^4 = 2.515$ e-11 M^4
$Z = 0.098 * d^3 = 0.098 * 0.00476M^3 = 1.057$ e-8 M^3

W (equivalent Load) $= dL * 12 * E*I / (L^3)$
$W = 601e-6 * 114 e9 * 2.515$ e-11 $/ 0.1628^3$
$W = 4.8$ N

Stress due to the 601 micron displacement =

$S = W * L / (2\ Z)$
$S = 4.8 * 0.1628 / (2*1.057e-8) = 36.9$ MPa

FEA shows average bipod stress of 2MPa for the -100C cases
Near the base of the bipod leg 40MPa was shown in the -133 C case
Yield strength of the Ti-6Al-4V is $= 1100$ MPa

Calculating the Radiation Heat Load Incident on the Front of the Focal Plate:

The warm front fused silica vacuum window radiates heat to the cold focal plate.

Q= Area * emissivity surfaces * Stefan-Boltzman Constant * (T1^4 – T2^4)

Diameter of C5 lens = 0.48 meters
Area of C5 lens = 0.181 M^2

Emissivity of the both the silicon and the glass surfaces are assumed 1 for a conservative approach. In reality the silicon is about 0.85

Stefan-Boltzman constant = 5.67e-8 W/M^2.K^4

T1 temperature of the glass = 277 K
The glass cools due to lack of conduction the rest of the vessel.

T2 temperature of the focal plate = 140K in the coldest case.

Q = 0.181 * 5.67e-8 * (277^4 -140^4) = 56 W

The heat load applied to the front of the Focal Plate in all of the FEA models is
290 W/M^2 with a 0.216 m^2 area focal plate = 63 Watts

The additional heat load approximates additional heat load from the other surfaces of the focal plate and the electronic heat load. More detailed thermal calculations will be given in other reports.

Calculating the Deflection of a Round Plate Supported at the Edges:

Using Roark and Young 6th Edition case #10 Table 24:
The deflection due to gravity of a round focal plate simply supported at the edges is calculated.

$Y_c = -qa^4/64D$

Where:
q = pressure on the plate
Focal Plate weighs 26 lbs without CCDs / 335 inch^2 area of focal plate
q= 0.077 psi
a = radius of focal plate = 10.33 inches
D= $Et^3 / (12(1-v^2))$
Where:
E= young's modulus = 10e6 psi for aluminum
T= thickness of the plate = 1.38 inches
V= Poisson's ratio for aluminum = 0.33
D= 10 e6 psi * 1.38 ^3 / 12(1-.33^2) = 2.46 e6

Y_c = 0.077 * 10.33^4 / 64 * 2.46e^6
Y_c = 5.5 e-6 inches
Y_c = 0.14 microns

No significant deflection on the focal plate is expected due to gravity loading.

Calculating the Deflection of a Round Plate due to a thru thickness temperature gradient:

Using Roark and Young 6th Edition case #15 Table 24:
The deflection due to gravity of a round focal plate simply supported at the edges is calculated.

$Yc = Ky * CTE * dT\ a^2 / t$
Where:
$Ky = .5$ for thickness with a uniform gradient
CTE of Aluminum 6061 = 22 e-6 m/m C
$dT = 1\ °C$ thru the gradient thickness
a = radius of focal plate = 10.33 inches = 0.2625 meters
t= thickness of the focal plate = 1.38 inches = 0.035 meters

$Yc = 0.5 * 22e-6 * 1 * 0.2625^2 / 0.035$
$Yc = 2.16\ e-5$ meters
$Yc = 21$ microns

A 4 micron flatness of the focal plate was observed in the FEA results.

The actual gradient thru the focal plate is smeared over the surface and not uniform.

The flatness of the focal plate is reduced because the bipods apply a moment to the focal plate that helps flatten the focal plate.

Switching the focal plate material from Aluminum to Molybdenum would flatten the focal plate by about a factor of 4 due to its smaller CTE coefficient.

Summary of FEA Results:

Case 1)
Boundary Conditions: Focal plate -100°C, Ambient Temperature 20 °C, gravity vertical (telescope vertical), 45 watt heat load on the front surface of the focal plate.
Results: Focal plate Z position moves 142 microns away from the C5 lens. Focal plate flatness 4 microns Peak to Peak.

Case 2)
Boundary Conditions: Focal plate -100°C on 8 cold fingers, -101 °C on outside 4 cold fingers, Ambient Temperature 20 °C, gravity vertical (telescope vertical), 45 watt heat load on the front surface of the focal plate.
Results: Focal plate Z position moves 142 microns away from the C5 lens. Focal plate flatness is 4 microns Peak to Peak.

Case 3)
Boundary Conditions: Focal plate -100 °C, Ambient Temperature 20 °C, gravity horizontal (telescope horizontal), 45 watt heat load on the front surface of the focal plate.
Results: Focal plate Z position moves 145 microns away from the C5 lens. Focal plate flatness is 5 microns Peak to Peak. Lateral translation of the focal plate 16 microns.

Case 4)
Boundary Conditions: Focal plate -100 °C, Ambient Temperature -10 °C, gravity vertical (telescope vertical), 45 watt heat load on the front surface of the focal plate.
Results: Focal plate Z position moves 152 microns away from the C5 lens. Focal plate flatness is 4 microns Peak to Peak. The focal plane moves more in Z than the ambient case since the average temperature of the bipods decreased.

Case 5)
Boundary Conditions: Focal plate -133 °C, Ambient Temperature 20 °C, gravity Vertical (telescope vertical), 45 watt heat load on the front surface of the focal plate.
Results: Focal plate Z position moves 166 microns away from the C5 lens. Focal plate flatness is 1 microns Peak to Peak. The focal plane moves more in the Z direction than the ambient case since the average temperature of the bipods decreased.

Appendix A – FEA Results

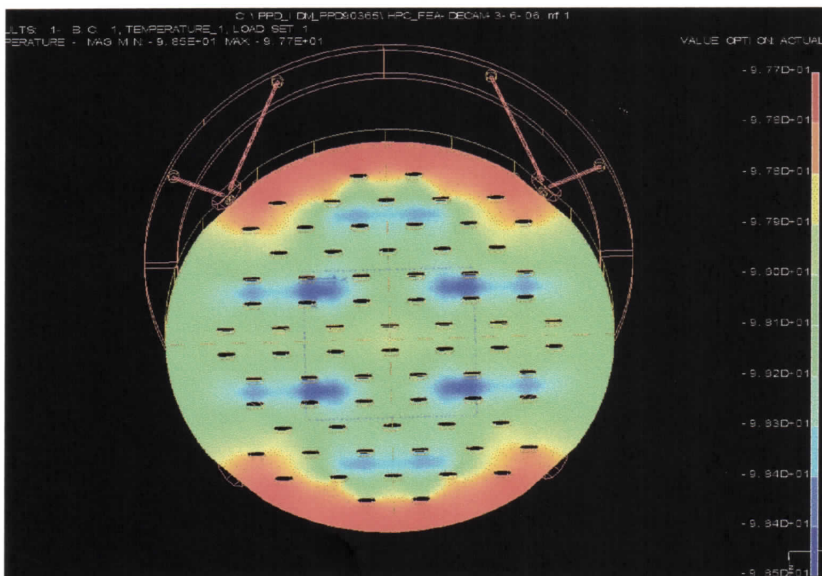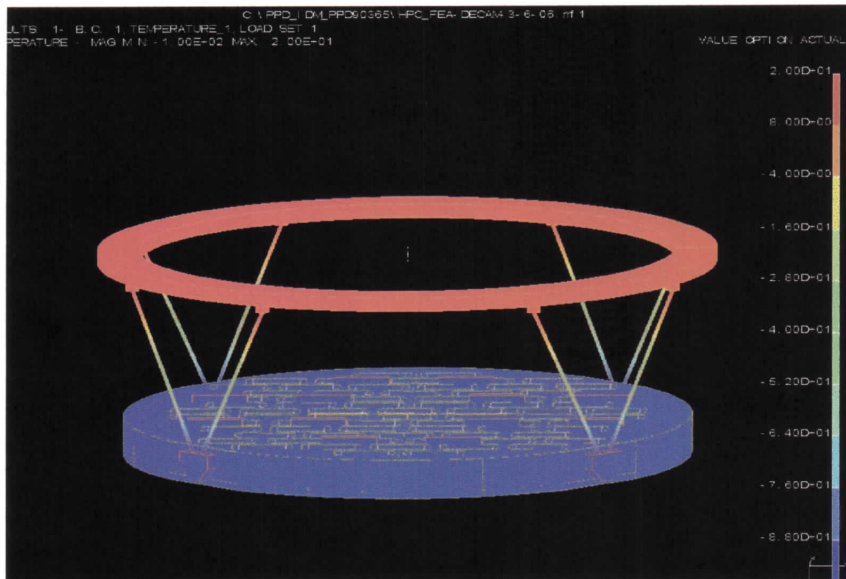# CASE 1, Focal Plate -100 ℃
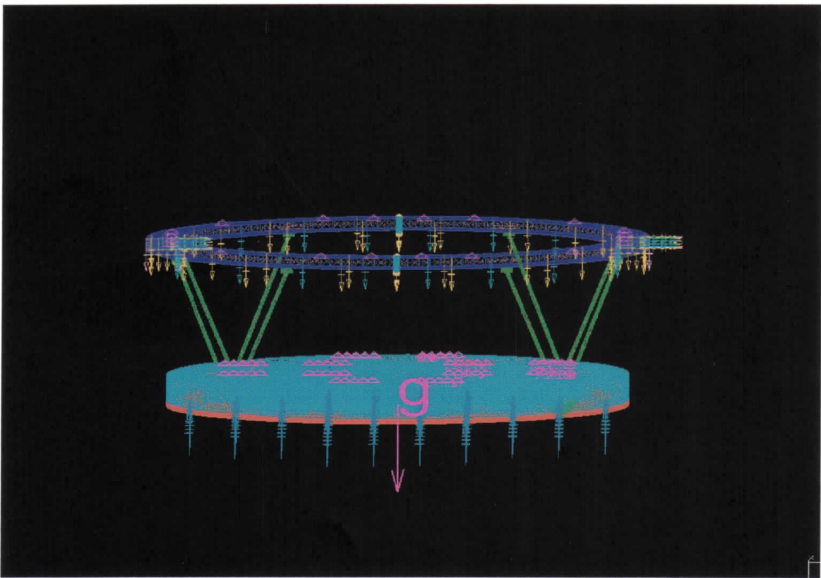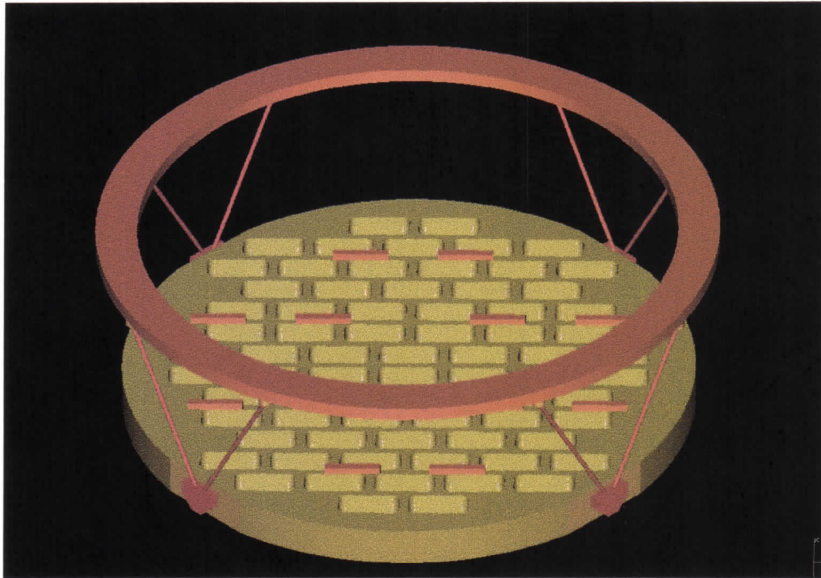
Parameters and Boundary Conditions:
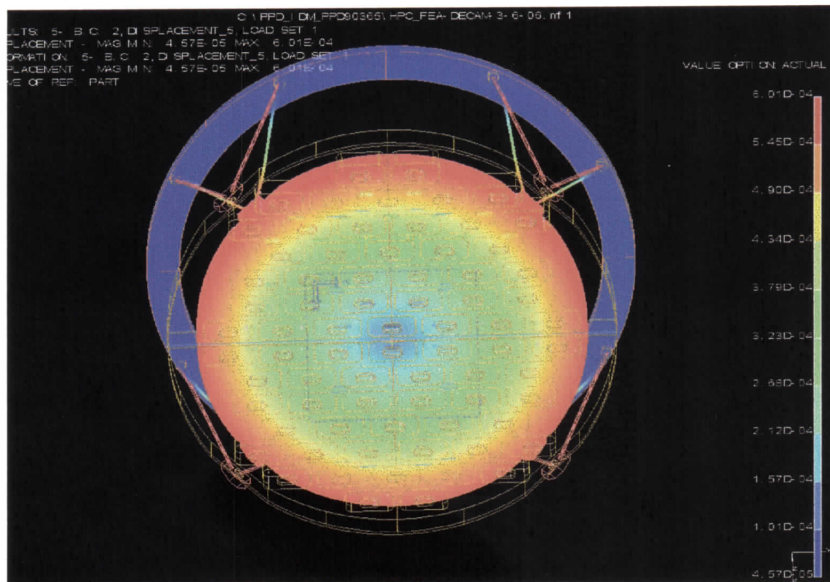
Aluminum 1.38 inches thick

Temperature loading on focal plane (-100 ℃ at all cold fingers)

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ on the upper bipod support ring

Parameters and Boundary Conditions:

Temperature Gradient

Aluminum 1.38 inches thick

Temperature loading on focal plane (-100 ºC at all cold fingers)

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ on the upper bipod support ring

-100ºC applied at cold finger interface

Red = -97.7 ºC, blue -98.5ºC

Parameters and Boundary Conditions:
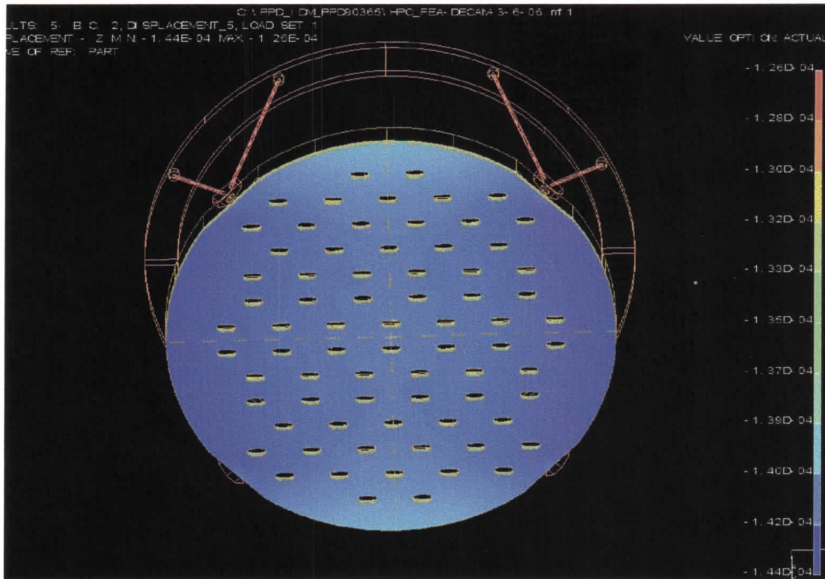Aluminum 1.38 inches thick
Distortion magnitude due to temperature
Gravity in Z direction
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at bipod ring
-100°C applied at cold finger interface
Red = 601 microns, blue 0

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

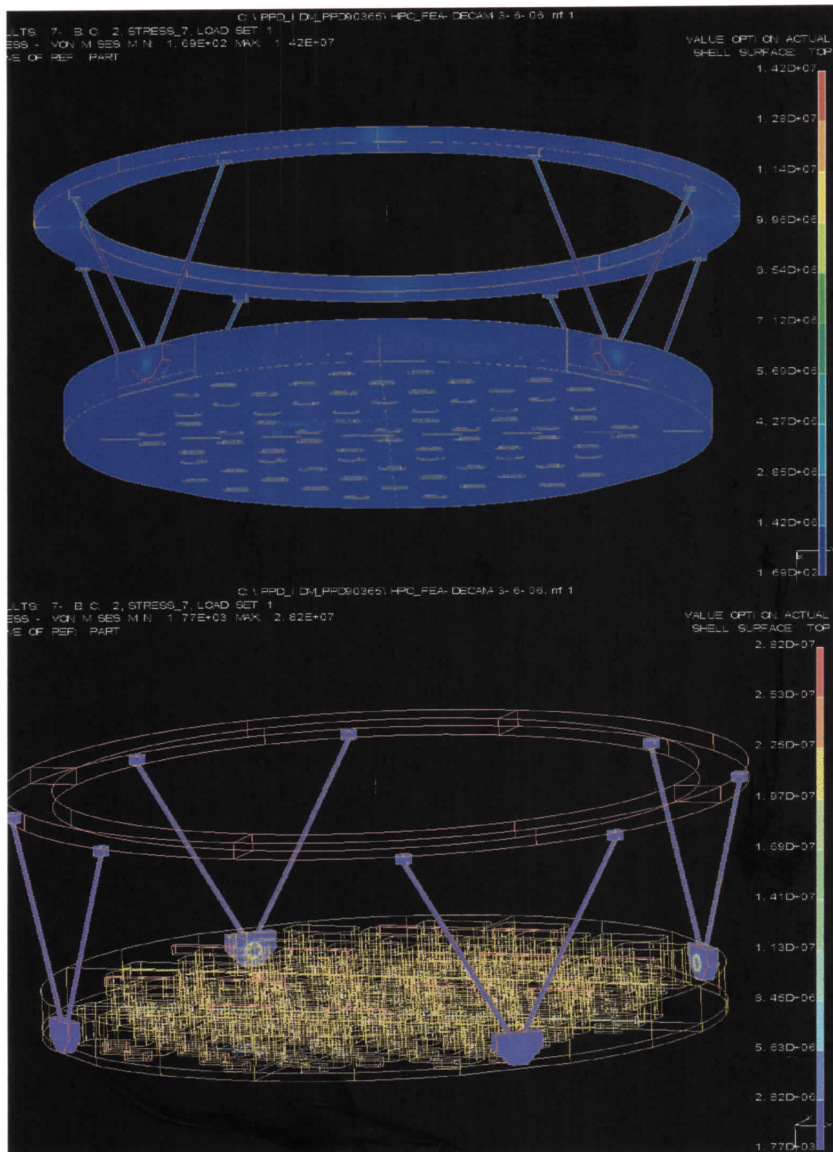Z displacement due to temperature, only front of focal plate plotted

Gravity in Z

0.007 w/m^2 (2 watts total) on bipods

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at bipod ring

-100°C applied at cold finger interface

Light blue = 140 microns, blue 144 microns

Parameters and Boundary Conditions:
Aluminum 1.38 inches thick
Stresses are plotted,
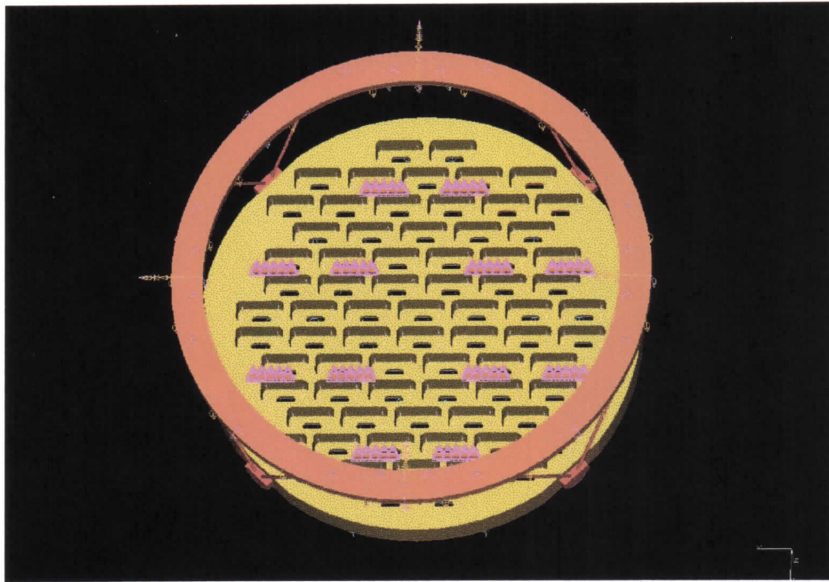Gravity in Z
0.007 w/m^2 (2 watts total) on bipods
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at bipod ring
-100°C applied at cold finger interface
Light blue = 28 megapascals at the ti-al joint. Max in the bipod leg 2 e6 pa

CASE 2, TEMP PROFILE, 4 COLD FINGERS at -101 ºC REMAINDER AT -100 ºC
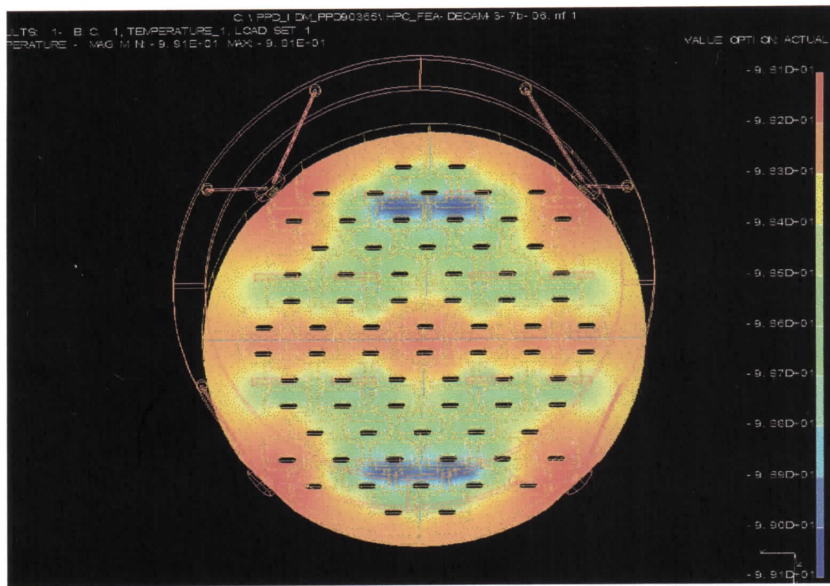
Parameters and Boundary Conditions:
Aluminum 1.38 inches thick
Temperature loading on focal plane (-100 ℃ at all cold fingers)
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ on the upper bipod support ring
-100℃ applied at cold finger interface, 4 cold fingers at -101℃. In this picture the top
and bottom 2 cold finger joints (magenta) are set at the lower temperature.

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

Temperature profile of the front face of the focal plate.
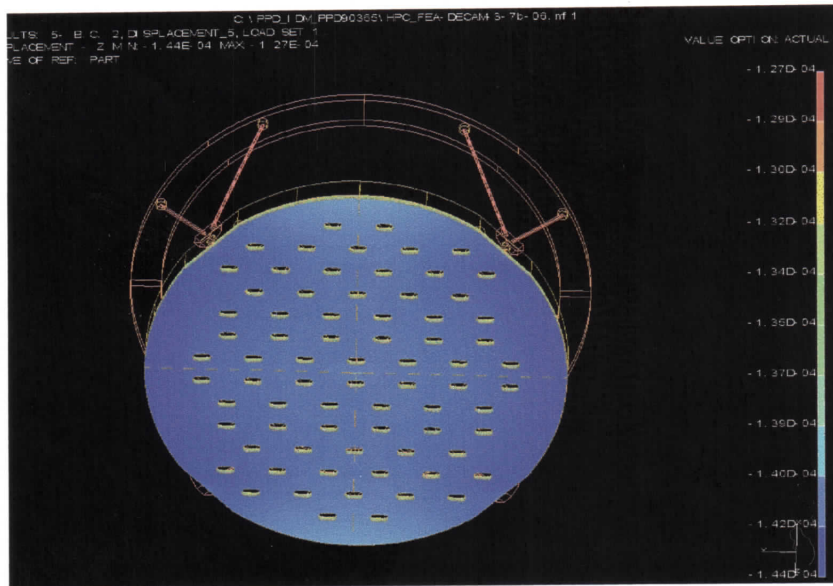
Gravity in Z

$0.007 \ w/m^2$ (2 watts total) on bipods

$290 \ w/m^2$ applied to the front face ~63 watts on face

Supported in XYZ at bipod ring

-100°C applied at cold finger interface, 4 cold fingers at -101°C.

red = -98.1 °C, blue -99.1 °C

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

Z displacement due to temperature, only front of focal plate plotted

Gravity in Z

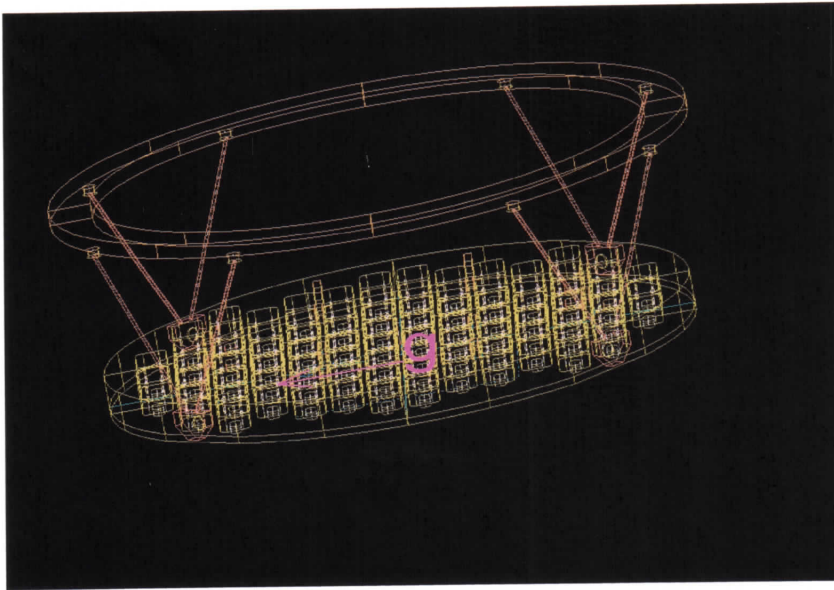0.007 w/m^2 (2 watts total) on bipods

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at bipod ring

-100°C applied at cold finger interface 4 at -101°C

lightblue = 141 microns, blue 144 microns

CASE 3, Changing Gravity from Vertical to Horizontal

Parameters and Boundary Conditions:
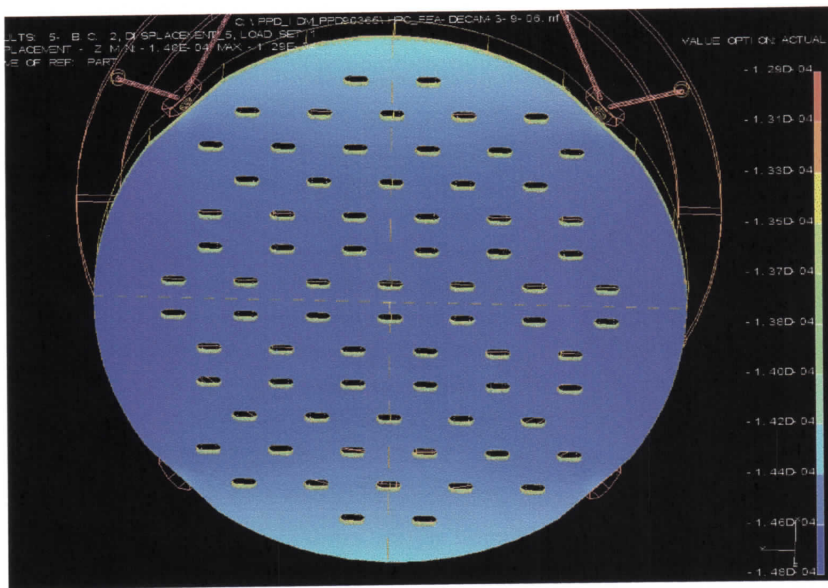
Aluminum 1.38 inches thick

Gravity in X (horizontal)

Temperature loading on focal plane (-100 ºC at all cold fingers)

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at bipod support ring

-100ºC applied at cold finger interface

Temperature distribution same as -100ºC case

Parameters and Boundary Conditions:

Distortion in Z of the focal plate front face.

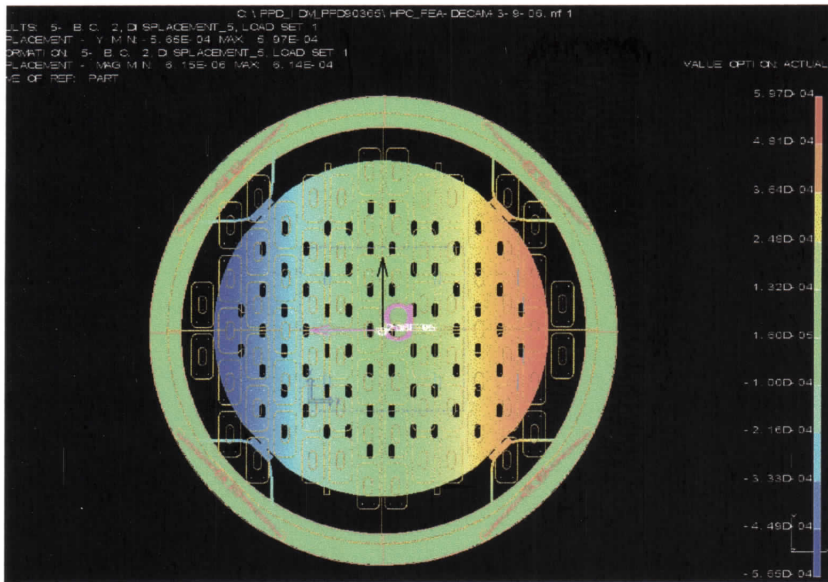Aluminum 1.38 inches thick

Gravity in x (horizontal)

Temperature loading on focal plane (-100 °C at all cold fingers)

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

Temperature distribution same as -100°C case

lightblue = 143 microns, blue 148 microns   -bipod stress ~2e7 Pa

Parameters and Boundary Conditions:

Distortion in X plotted

Aluminum 1.38 inches thick

Gravity in x (horizontal)

Temperature loading on focal plane (-100 °C at all cold fingers)

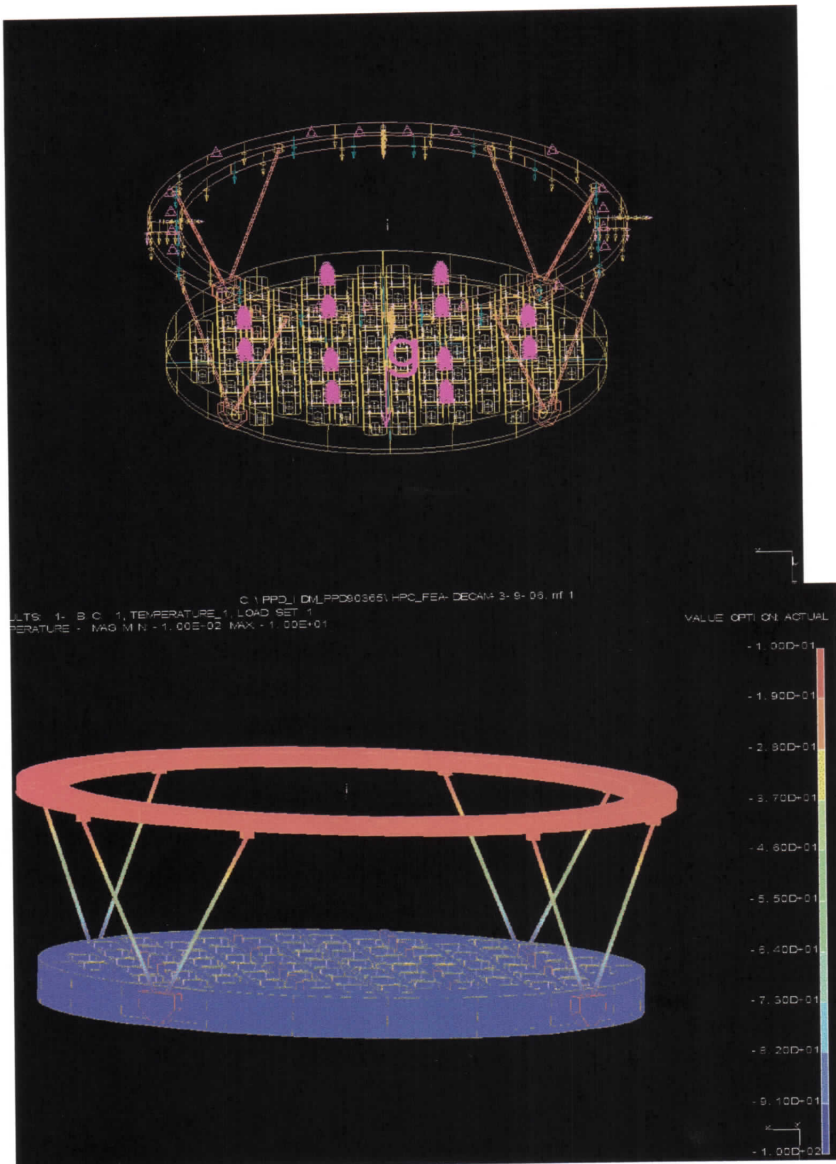290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

-100°C applied at cold finger interface

Temperature distribution same as -100°C case

red = 597 microns, blue 565 microns,   center point 16 microns offcenter

CASE 4, Changing the Ambient Temperature from 20 ℃ to -10℃

Parameters and Boundary Conditions:
Temperature profile plotted
Aluminum 1.38 inches thick
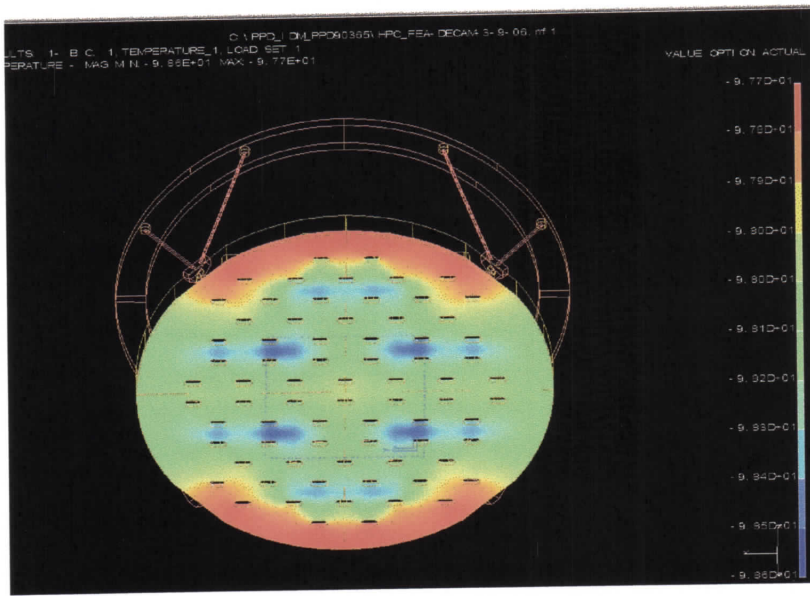Z displacement due to temperature, only front of focal plate plotted
Gravity in Z
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at the bipod support ring
-100°C applied at cold finger interface
Upper ring at -10°C

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

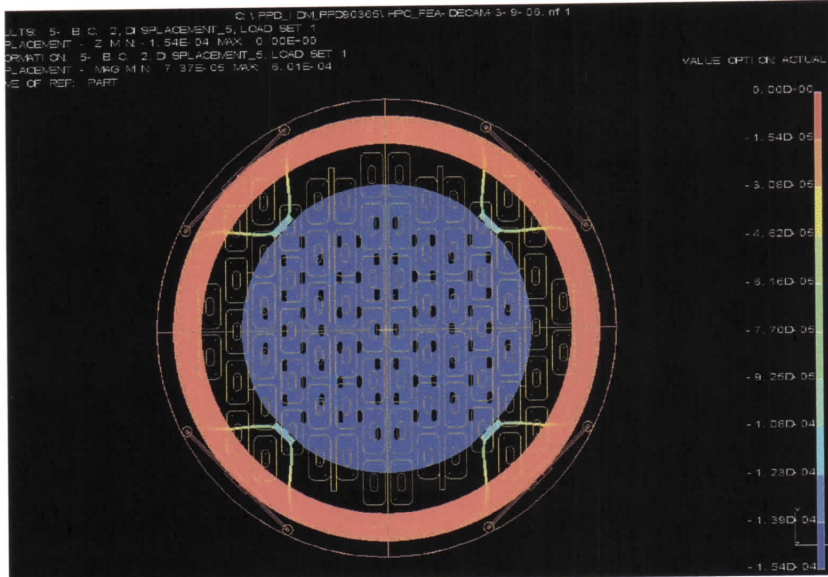Temperature Profile, only front of focal plate plotted

Gravity in Z

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

-100°C applied at cold finger interface

Upper ring at -10°C

red = -97.7 °C, blue -98.6° C

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

Z displacement due to temperature,

Gravity in Z
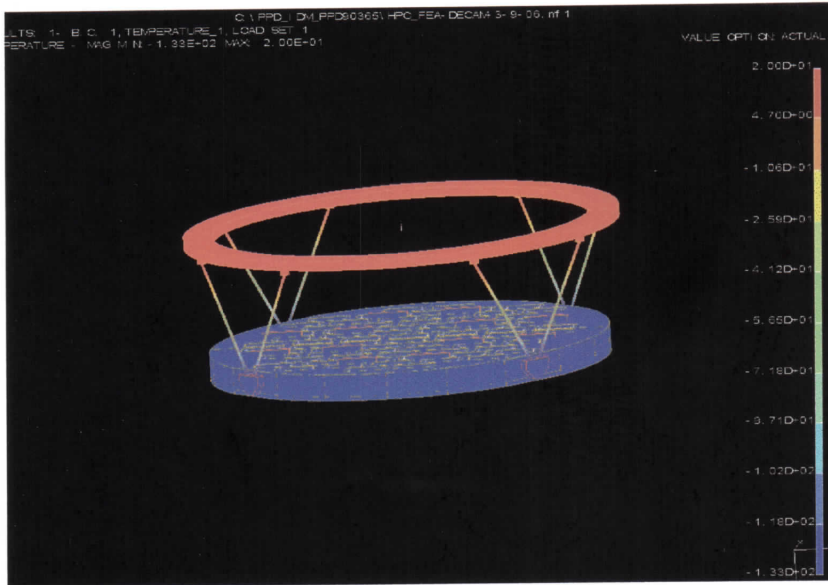
290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

-100°C applied at cold finger interface

Upper ring at -10°C

Distortions exaggerated

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

Z displacement due to temperature, only front of focal plate plotted

Gravity in Z

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

-100°C applied at cold finger interface

Upper ring at -10°C

lightblue = 150 microns, blue 154 microns   -bipod stress ~1.9e7 Pa

CASE 5, Changing the Focal Plate Temperature from -100ºC to -133 ºC

Parameters and Boundary Conditions:
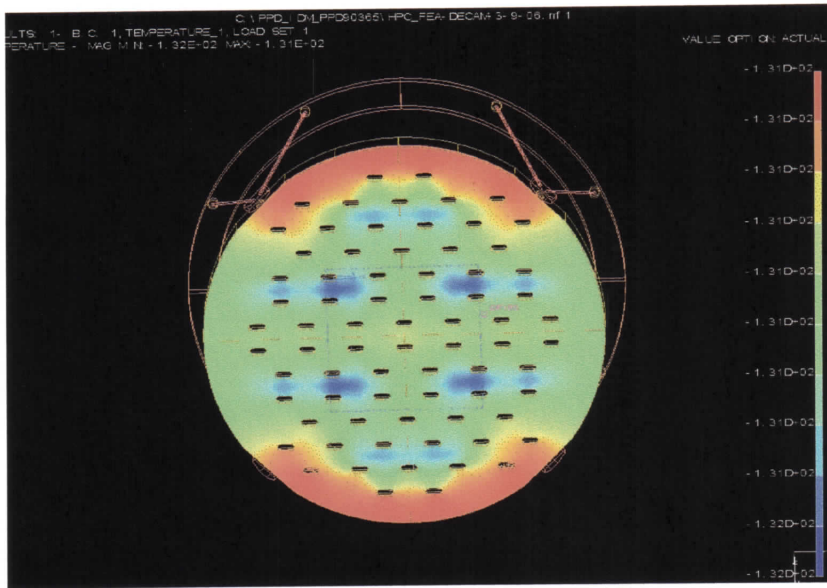Aluminum 1.38 inches thick
Temperature profile is plotted
Gravity in Z
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at the bipod support ring
-133°C applied at cold finger interface
Upper ring at 20°C

Parameters and Boundary Conditions:
Aluminum 1.38 inches thick
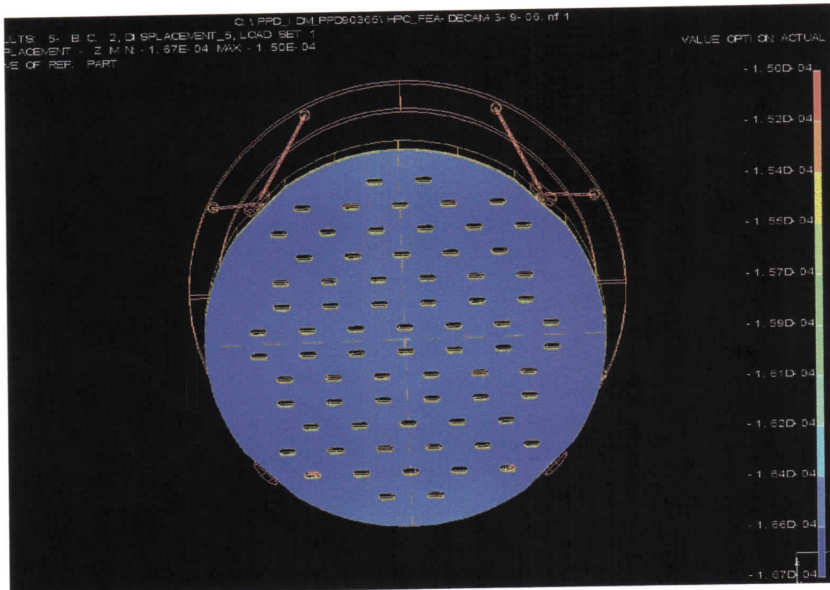Temperature profile, only front of focal plate plotted
Gravity in Z
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at the bipod support ring
-133°C applied at cold finger interface
Upper ring at 20
Red = -130.8 °C blue = -131.5°C

Parameters and Boundary Conditions:

Aluminum 1.38 inches thick

Z displacement due to temperature, only front of focal plate plotted
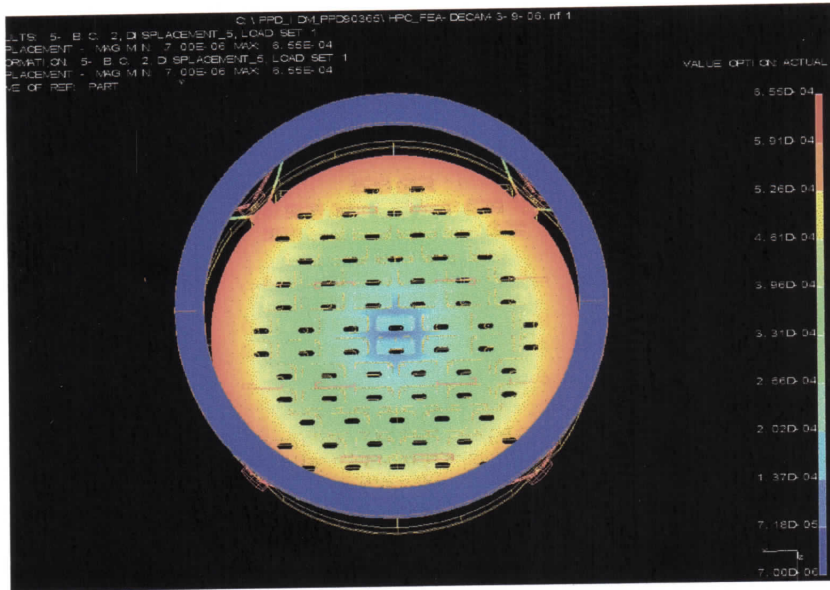
Gravity in Z

290 w/m^2 applied to the front face ~63 watts on face

Supported in XYZ at the bipod support ring

-133°C applied at cold finger interface

Upper ring at 20

blue = 166 microns flat within 1 Z displacement only

Parameters and Boundary Conditions:
Aluminum 1.38 inches thick
Magnitude distortions plotted
Gravity in Z
290 w/m^2 applied to the front face ~63 watts on face
Supported in XYZ at the bipod support ring
-133°C applied at cold finger interface
Upper ring at 20
Red = 655 microns

Max bipod stress = 20 MPA